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E.I. ASINOVSKIY AND V.I. SHABASHOV

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AN EXPERIMENTAL INVESTIGATION OF THE COEFFICIENTS OF ELECTRIC CONDUCTIVITY AND THERMAL CONDUCTIVITY OF PLASMA IN AIR

E.I. Asinovsliy and V.I. Shabashov

ABSTRACT: The authors build equipment to represent a constant current arc stabilized by a wall in air under atmospheric pressure. They obtained data about the coefficient of electrical conductivity in the temperature interval 700 - 11,000°K and about the coefficient of thermal conductivity in the temperature interval 6000 - 14,000°K.

The problem of heatshielding in aircraft entering the atmosphere of a planet at high velocities has given rise to a large number of investigations of the transfer characteristics of such gases as N_2, CO_2, their mixtures and air. /217*

In a number of works, devoted to calculation of the transfer characteristics of N_2 and air [1-5], there is considerable disagreement in the data about the coefficient of thermal conductivity. A detailed analysis of this disagreement is not the purpose of this article.

There are two methods for experimental verification of the data on thermal conductivity of plasma.

In the first method an arc discharge is used to measure the coefficient of thermal conductivity [6-8].

The second method proposes the measurement of the total heat flow at the critical point of a body streamlined by a plasma behind a shock wave and a comparison of this value with the calculated value [9-11].

References [12, 13] give the most complete survey of these results for air and N_2, as obtained in shock tubes. Reference [13] shows that, in the first place, the heat flow depends mainly on the value of the thermal conductivity of the gas near the wall, since the presence of a thermal conductivity minimum of N_2 and air in the temperature range 9000-10,000°K leads to the appearance of a layer of gas with a comparatively low thermal conductivity, which effectively insulates the surface from the high-temperature gas which flows at the outer boundry of the boundary layer. In the second place, uncertainty of the value of the coefficient of thermal conductivity in the region of the ionization maximum of even an order of magnitude leads to an uncertainty in the heat flow of only

*Numbers in the margin indicate pagination in the foreign text.

a factor of two. In connection with this fact, according to the data obtained in shock tubes, it is difficult to evaluate the value of the coefficient of thermal conductivity in the temperature range higher than 10,000°K.

Reference [12], in contrast to the opinions of the authors of reference [14], asserts that nitrogen can never be examined as an adequate model of air for calculating the heat flow, since the latter is basically determined by the thermal conductivity of the gas in the temperature range T < 8000°K, i.e., in the range where there is the most significant difference between the thermal conductivity of nitrogen and air, as determined by the reaction component.

References [5,16] were published recently and pointed out the difference between the thermodynamic and transfer characteristics of a mixture of reacting gases with a temperature gradient and the equilibrium characteristics. This difference arises from the separation of the components by diffusion. /218

An evaluation of the influence of the component separation effect on the thermal conductivity of air [15] showed that this influence can be especially great in the temperature range in which dissociation takes place.

The thermal conductivity of nitrogen was investigated in a number of experiments [6-8, 17] using a stabilized electric arc. At the present time we can assume that the coefficient of thermal conductivity for nitrogen is reliably known for the temperature range 6000-15,000°K. The experimental data show the best correlation with calculations of [4].

With reference to air, we know only one experimental reference on the determination of the coefficient of thermal conductivity [18] for the temperature range 1000-5000°K. This determination was made on a shock tube.

Comparison of these data with the calculation of reference [20], in which the potential of the heat flow is given as a function of temperature, showed a strong correlation.

It is interesting to investigate the thermal conductivity of air in the presence of a high temperature gradient from the point of view of assessing the influence of diffusion separation of the components of air on its thermal conductivity. A similar calculation is the purpose of this article.

The Experimental Equipment. To solve this problem we used a method for determining the electrical conductivity in an electric arc. The essence of this method is as follows. In the absence of convective heat transfer in the column of an arc, the temperature field in the arc can be described by the equation [21].

$$\operatorname{div} \lambda \operatorname{grad} T - \operatorname{div} \bar{F}^{rad} + \sigma E^2. \tag{1}$$

Integrating equation (1) on the assumption that the energy removal from the arc due to thermal conductivity takes place only in a radial direction, and solving it with respect to λ, we obtain

$$\lambda = \frac{1}{-rdT/dr} E_0^2 \int_0 \sigma r dr - \frac{1}{-rdT/dr} \int_0 r \operatorname{div} \bar{F}^{rad} dr. \tag{2}$$

The important role of radiation in the mechanism of heat removal from stabilized electric arcs in argon and nitrogen was proven in a number of references [6, 7, 22, 23].

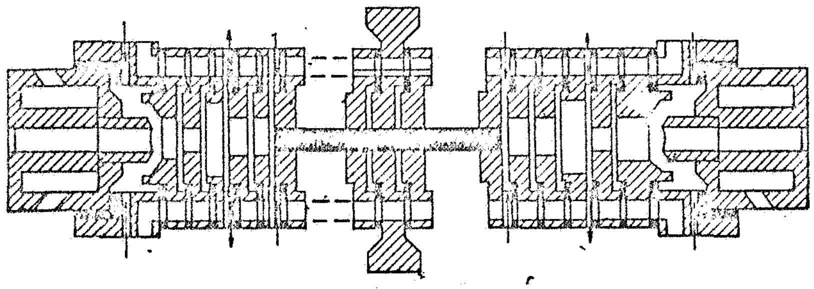

Fig. 1: A Diagram of the Equipment

To determine the coefficient of thermal conductivity according to equation (2), we must measure the strength of the electric field in the column of the arc E', the temperature distribution by radius of the column and the known functions $\sigma(T)$ and div $\bar{F}^{rad}$ (r).

The equipment was a stabilized electric arc [6,24]. Figure 1 shows a diagram of the equipment. The basic element of the equipment was a copper diaphragm 4 mm thick, cooled around the periphery /219
by water with a hole drilled in the center. The holes of a bank of these diaphragms form a channel, in which an electric arc of a constant current is struck. The diaphragms were insulated by spacers made of Teflon 4.

In order to make spectrascopic investigations, we included in the complex of stabilizing diaphragms a special diaphragm with a split, placed in the central part of the apparatus (cf. Fig. 1).

The electrodes would not operate in the air due to strong burning and, as a result, the spaces between the diaphragms became blocked with the erosion products of the electrodes and the apparatus became inoperative. In connection with this problem, we used an argon electrode shield [25]. Argon was supplied through special diaphragms with apertures. The exhause site of the argon-air mixture is shown in the diagram.

The diameter of the stabilizing channel in the operating part was 5 mm. The electrodes were made of tungsten and molded into a well-cooled head. A center boring was used to activate the equipment in the cathode. The equipment operated stably for several hours with currents I = 30-120 amp and for short periods sustained currents of up to 160 amps. Striking was accomplished in argon, after which the argon in the examined section was replaced by air; the absence of argon was controlled by the disappearence of its spectral lines.

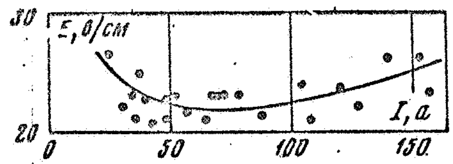

Fig. 2: The Strength of the Electric Field in the Air Arc as a Function of Current; d = 5 mm.

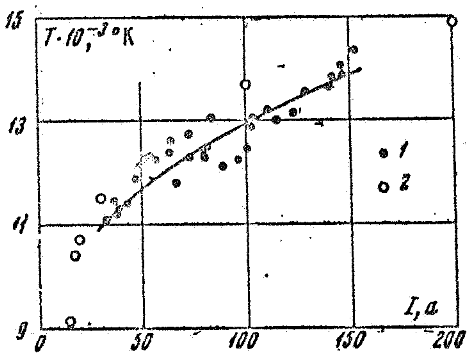

Fig. 3: The Axial Temperature of the Air Arc as a Function of Current for d = 5 mm: (1) The Data of the Authors; (2) Maecker's Data.

The gas flow rate was 14 n cm^3/sec for each intake. As a feed source we used a rectifier on VK-200 silicon diodes with a voltage of 500 V.

Electricity and Temperature Measurements. The strength of the electronic field was measured from the slope of the rectolinear part of the potential distribution along the column of the central part of the arc. The procedure of similar experiments in nitrogen and argon is presented in detail in reference [6,22]. The Measuring current, chosen from the diaphram probes was maintained at 10 amps. As in references [6,7] we detected no dependence of the probe potential on the value of the chosen current.

In the measuring scheme we used: a type M502 (class 0.1) voltmeter, a type M104 milliamperemeter (class 0.2) and a bank of RSP rheostats. The arc current was measured by the value of the voltage drop on a calibrated resistor using a PP - 1 potenti-

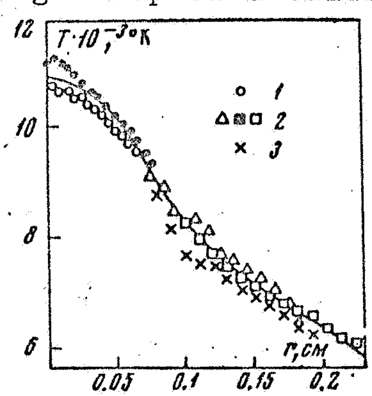

Fig. 4

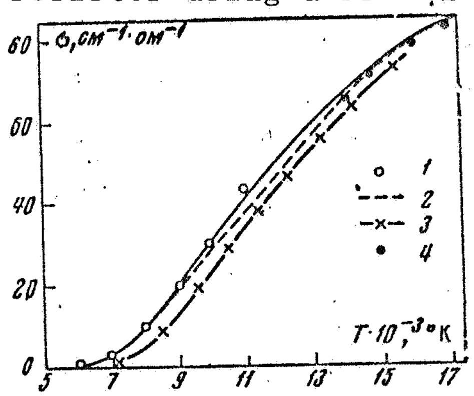

Fig. 5

Fig. 4: Radial Temperature Distribution in the Air Arc with a Current I = 30 amp; d = 5 mm: (1) NI 4935 Å; (2) Edge 3916 Å; (3) Edge 3371 Å.

Fig. 5. The Electrical Conductivity of Air as a Function of Temperature: (1) The Data of the Authors; (2) Nitrogen [6]; (3) Air, Calculation [1]; (4) Spitzer [32].

ometer. As a calibrated resistor we used a class 0.2 shunt (300 amp, 75 mv). Figure 2 shows the strength of the field in the column of the air arc as a measured function of the current strength.

The mean variance of the experimental points from the averaged curve is ~ 10%.

We used two methods to measure the temperature distribution.

In the axial zone of the air arc temperature measurement was made according to the absolute intensity of the N I 4935 Å line.

The spectrum was photographed using a DFS-13 diffraction spectrograph with a reverse dispersion of 4 Å/mm on a panchromatic photographic plate. To do this the image of the slit of the optical diaphragm was projected on the intake slit of the instrument with a condensor with F = 150 mm with a threefold increase. As a standard of brightness we used a weak-current carbon arc [26]. /220

The intensity of the N I 4935 Å line was computed for radiation from an optically thin layer. We used a computation of the composition of air [27], the probability of transfer was taken to be $A_m^n = 1.61 \cdot 10^6\ \mathrm{sec}^{-1}$ [28]. Figure 3 shows the temperature on the axis of the arc as a function of the current strength, obtained by the proposed method. The maximum variance from the averaged curve is approximately ± 500°K.

In the peripheral zone of the arc the temperature was measured by the intensity of the edge of the 3914 Å line of the 0-0 band of the first negative system of N^+_2, and the 3371 Å line of the 0-0 band of the second positive system of N_2 by the Larens method [29]. This method allows us, as we know, under certain conditions[1] to obtain the temperature distribution in the arc on the basis of relative measurements of the curve of the intensity of the edge. Figure 4 shows the temperature profile for the current I = 30 amp. The temperature values, measured by various methods, correlate well with each other.

Since the measurements were made laterally across the column of the arc in treating the data we made corrections related to the solution of the Abel equation [30].

Electrical Conductivity. To determine the coefficient of electrical conductivity, we took the electrical conductivity as a function of the temperature in the form of a third degree polynomial

$$\sigma(T) = AT + BT^2 + CT^3 \qquad (3)$$

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[1] The Maximum of the radiation coefficient must be outside the axial zone of the arc.

which was substituted into the relationship

$$I_t = 2\pi E_t \int_0^R \sigma r dr, \tag{4}$$

written for currents I = 30, 60 and 100 amps. The measurements of the temperature profiles of these currents was made with special care. The coefficients A, B, C were determined by the numerical solution of a system of three equations.

The maximum temperature on the axis of the arc (with a current of 100 amps) reached 12,600°K. Therefore, the most important contribution to the integrals of expressions of the type of (4) is made by the temperature range from 7000 to 1100°K. For this reason the obtained analytic relationship between the coefficient of /221
electrical conductivity and temperature can be used only for the indicated temperature range. In the temperature range above 13,000°K the electrical conductivity was computed by the Spitser theory, and for temperatures from 11,000 to 13,000°K the relationship between electric conductivity and temperature was obtained by interpolation.

The function σ (T) (Fig.5) was used to determine the coefficient of electrical conductivity.

For comparison, Figure 5 shows the coefficient of electrical conductivity for nitrogen as a function of temperature [23] and the computed function for air [1].

Results of the Measurements of Thermal Conductivity. The methods of determining the coefficient of thermal conductivity in the regions of the dissociation and ionization maxima differ from one another. To determine thermal conductivity in the region of the dissociation maximum we used a temperature distribution by radius for the lowest of the attained currents I = 30 amps (Fig. 4). The temperature on the axis of the arc for this current was T_0 = 10,900°K. The role of radiation in the heat transfer with T = 11,000 °K is insignificant [6]. Therefore we can ignore the second term in the right-hand side of equation (2). The expression for determing λ has the form

$$\lambda = \frac{1}{-r dT/dr} E^2 \int_0^r \sigma r dr. \tag{5}$$

The value of dT/dr can be determined graphically by differentiating the temperature profile. To determine the coefficient of thermal conductivity in the region of the ionization maximum we used the

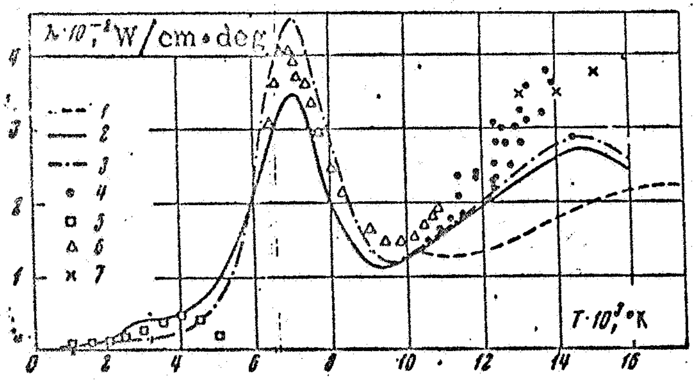

Fig. 6: The Thermal Conductivity of Air as a Function of Temperature: (1) Calculation, Air [1]; (2) Calculation, Air [4]; (3) Calculation, Nitrogen [4]; (4) Axial Data, Air, This Article; (5) Air [18]; (6) The Authors' Data, Radial Temperature Distribution for I = 30 amps; (7) Axial Data, Nitrogen [6].

method of references [6,22]. According to the results of [22], equation (2) for the axial area can be written in the form:

$$\lambda(T_0) = \sigma(T_0)E^2 / 2T_0'' - \operatorname{div} F_{05}^{rad} / 2T_0''. \quad (6)$$

Here the value $T_0'' = 2(T_0 - T)/r^2$ is determined from the slope of the rectolinear part of the temperature distribution as a function of r^2 and div $\bar{F}_{05}^{rad}$ (the divergence of the radiant flux on the axis of the arc with a diameter of the stabilizing channel d = 5 mm.

The value of div $\bar{F}_{05}^{rad}$ as a function of temperature was taken from reference [6] for nitrogen. According to careful evaluations, the value of the divergence of the radiant flux for an air arc differs insignificantly from the data of reference [6].

Figure 6 shows the results of the measurements of thermal conductivity by the two methods.

The maximum relative error in the measurement of λ was estimated at 50% [22]. For comparison this figure shows the experimental data of the thermal conductivity of air [20] and nitrogen [6] and also the results of the calculations [1,4]. /22

Discussion of the Results. It is clear from Figure 6 that, within the margin of error our data about the thermal conductivity of air in the temperature range 6000 - 14,000°K correspond well with the calculated data of reference [20], computed on the assumption of thermodynamic equilibrium in the system. This result indicated the absence of any influence of the temperature gradient on the composition of the plasma in the arc within the margin of error of the measurement of λ in the investigated range.

It would be very interesting to investigate thermal conductivity in the dissociation region of oxygen, since, according to the evaluations of reference [15], it is in this region that the influence of the effect of diffusion separation of the components of air is the greatest. In addition, a temperature on the order of 4000°K is reached near the wall of the stabilizing channel of the arc, i.e., at the place where the temperature gradient is the highest.

In conclusion the authors would like to thank A. Ye. Sheydlin and A.V. Kirillin for their active interest in our work and their useful discussions and N.A. Grineva and V.L. Nizkovskiy for their assistance in the interpretation of the experimental data.

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